Earth Observing System AM1 Mission to Earth

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***Abstract*— In 1998, NASA launches EOS-AM1, the first of a series of the Earth Observing System (EOS) satellites. EOS will monitor the evolution of the state of the earth for 18 years, starting with the morning observations of EOS-AM1 (10:30 a.m. equatorial crossing time). An integrated view of the earth, as planned by EOS, is needed to study the interchange of energy, moisture, and carbon between the lands, oceans, and atmosphere. The launch of EOS-AM1 and other international satellites marks a new phase of climate and global change research. Both natural and anthropogenic climate change have been studied for more than a century. It is now recognized that processes that vary rapidly in time and space—e.g., aerosol, clouds, land use, and exchanges of energy and moisture—must be considered to adequately explain the temperature record and predict future climate change. Frequent measurements with adequate resolution, as only possible from spacecraft, are key tools in such an effort. The versatile and highly accurate EOS-AM1 data, together with previous satellite records, as well as data from the Advanced Earth Observing System (ADEOS) (I and II), Tropical Rainfall Measuring Mission (TRMM), Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Along Track Scanning Radiometer (ATSR), Medium Resolution Imaging Spectrometer (MERIS), Environmental Satellite (ENVISAT), EOS-PM1, Land Remote-Sensing Satellite (Landsat), and ground-based networks is expected to revolutionize the way scientists look at climate change. This article introduces the EOS-AM1 mission and the special issue devoted to it. Following a brief historical perspective for an insight into the purpose and objectives of the mission, we shall summarize the characteristics of the five instruments onboard EOS-AM1. Specifically, we concentrate on the innovative elements of these five instruments and provide examples of the science issues that require this type of data. These examples show the importance of collecting data simultaneously from each of the five EOS-AM1 sensors for studying rapidly varying processes and parameters.**

***Index Terms*— Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), aerosol, anthropogenic forcing, atmospheric chemistry, biomass burning, carbon cycle, carbon dioxide, climate, climate change, clouds, Clouds and Earth's Radiant Energy System (CERES), Earth Observing System (EOS)-AM1, earth science, global change, global warming, greenhouse gas, land use, Measurements Of Pollution In The Troposphere (MOPITT), Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR), phytoplankton, predictive computer models, radiation budget, remote sensing, sea surface temperature, troposphere, vegetation.**

NOMENCLATURE

ADEOS	Advanced Earth Observing System (Japanese).
AirMISR	Airborne MISR simulator.
ARM	Atmospheric Radiation Measurement program.
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer.
ATSR	Along Track Scanning Radiometer.
AVHRR	Advanced Very High Resolution Radiometer.
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer.
BSRN	Baseline Surface Radiation Network.
CERES	Clouds and Earth's Radiant Energy System.
CFC	Chlorofluorocarbon.
CH_4	Methane.
CO	Carbon monoxide.
CO_2	Carbon dioxide.
CZCS	Coastal Zone Color Scanner.
DoE	Department of Energy.
ENVISAT	Environmental Satellite.
EOS	Earth Observing System.
EOS-AM1	First EOS spacecraft (launches 1998); crosses the equator at 10:30 a.m. in a descending polar orbit.
EOS-PM1	Second EOS spacecraft (launches 2000); crosses the equator at 2:30 p.m. in an ascending polar orbit.
ERBE	Earth Radiation Budget Experiment.
GOES	Geostationary Operational Environmental Satellite.
IPCC	Intergovernmental Panel on Climate Change.
IR	Infrared.
LAI	Leaf area index.
Landsat	Land Remote-Sensing Satellite.
LTER	Long-Term Ecological Research.
MAS	MODIS Airborne Simulator.
MERIS	Medium Resolution Imaging Spectrometer.
METEOSAT	Meteorological Satellite.
MISR	Multi-angle Imaging SpectroRadiometer.
MODIS	Moderate Resolution Imaging Spectroradiometer.
MOPITT	Measurements Of Pollution In The Troposphere.
NASA	National Aeronautics and Space Administration.
NSF	National Science Foundation.
POLDER	Polarization and Directionality of Earth's Reflectances.

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SeaWiFS	Sea-viewing Wide Field-of-view Sensor.
TOA	Top-of-the-atmosphere.
Topex-Poseidon	Ocean Topography Experiment.
TRMM	Tropical Rainfall Measuring Mission.
USGCRP	United States Global Change Research Program.
WCRP	World Climate Research Program.
WMO	World Meteorological Organization.

I. Introduction

WE RECOGNIZE that change—due to a host of natural causes and effects—has been the only constant in our planet's 4.5 billion year history. The earth's orbital mechanics, geological forces, biological processes, and feedback systems (driven by the dynamic nonlinear interchanges of energy, mass, and momentum) have perpetually kept its climate in a state of flux. These natural climate variations sometimes negatively impact humans and, as such, merit close scientific scrutiny if we are to better understand and predict their onset as well as mitigate their consequences on our living conditions. As recently as 1400 AD, the European settlements on Greenland were abandoned when average temperatures decreased by about 1.5 °C over a period of about two centuries during the Little Ice Age [1]. Within the last century, we have seen average global temperatures rise by 0.5 °C [1]. Is this recent increase due to natural variation, human activities, or a combination of both?

There is mounting scientific evidence, going back 100 years, that human activities have attained the magnitude of a geological force and have begun to impact climate on a global scale [2]. In that relatively short span, humans transformed about 40% of earth's land surface, changing its reflectance of sunlight and modifying its hydrological cycle [2]. Carbon dioxide concentrations in the atmosphere have increased by 30% since the beginning of the industrial revolution and continue to increase at an unprecedented rate [3], perturbing climate patterns and affecting global photosynthesis [4]–[7]. Humans introduced new man-made greenhouse gases into the atmosphere [8] that also destroy the stratospheric ozone layer. It is possible that the current warming trend, and the corresponding climate change, will continue and even accelerate given plausible projections of human activities. The threat of climate change lies not only in the temperature increase, but also in the redistribution of moisture, possibly causing droughts in some places and floods in others. Other possible effects include sudden (decadal) disruption of the thermohaline circulation/North Atlantic Deep Water formation, as has occurred in the past [9], with possible significant feedbacks on climate and ocean productivity. The nonlinear nature of the earth system is demonstrated in the research of the effect of man-made CFC's on the stratospheric ozone [10]. In this case, models predicted correctly the effect of CFC's on reduction of ozone concentrations, but failed to predict by an order of magnitude the loss of ozone over Antarctica in the spring time. The combination of CFC's, the presence of polar stratospheric clouds, and isolation of the polar stratospheric air was found to contribute to the ozone hole phenomenon.

The threat of human-induced climate change, despite scientific uncertainties, prompted the United Nations to hold a conference on climate change in Kyoto, Japan, in December 1997. The meeting further illustrated that efforts to control human impacts on climate are controversial, with potential social, economic, and political repercussions. Further scientific progress is needed to address: what is the human contribution to the current warming trend? What are the primary geophysical factors in this warming trend? Will the rising levels of greenhouse gases cause the earth's average temperature to increase at an accelerating rate? If so, what will be the regional and temporal effects of rising temperatures on precipitation patterns, sea level, human health, food production, inland water quality, biological productivity on land and in the oceans, and weather patterns?

To answer these questions, the earth science community must support a comprehensive program of observations from ground-based stations and remote-sensing platforms. Remote sensing from satellites is the only practical way to obtain continuous spatial and temporal fields of data needed for global modeling and change detection. Approximately 20 years of satellite data now available corroborate trends found in ground-based observations [11] and have provided a unique global view of the interactions between climate and the biosphere [4], [12]. Though scientists learned much from these satellite measurements, they are not complete and were often made by instruments not designed for the studies to which they were applied (e.g., AVHRR, GOES, and METEOSAT). Other satellite instruments (i.e., CZCS or ERBE) were built in the early years of earth remote sensor development and, therefore, are being replaced by more sophisticated instruments (i.e., SeaWiFS, MODIS, and CERES) that take advantage of newer technological innovations.

Today, through its Earth Science Enterprise, NASA is collaborating with a number of other governments worldwide to build a new generation of sensors that will address the measurement objectives identified by the United States Global Change Research Panel (USGCRP) and needed to reduce the uncertainty in climate prediction identified by the Intergovernmental Panel on Climate Change (IPCC). EOS is presently scoped to provide at least an 18-year data set that will allow us to distinguish between short-term anomalies, natural interannual to interdecadal climatic oscillations, and human-induced climate change. To meet the measurement objectives, EOS data will be collected over a wide spectral range at both high and moderate spatial resolutions with a variety of observation strategies, as described in Table I.

II. Historical Perspective

We are in the midst of an earth science revolution that will be fully realized with the 1998 launch of EOS-AM1—the flagship spacecraft of NASA's EOS (see Fig. 1). To place EOS-AM1's expected contributions to science into the proper perspective, it is useful to consider the 160-year history of climate research. Global climate investigations may have started in 1824 when Fourier published his paper describing the earth's atmosphere as having (what was later dubbed) a "greenhouse effect." He wrote that the atmosphere acts like

TABLE I
SUMMARY OF THE MAIN CHARACTERISTICS OF THE FIVE INSTRUMENTS ABOARD EOS-AM1

Instrument	ASTER	MODIS	MISR	CERES	MOPITT
Spatial resolution at nadir	15 m in visible, 30 m in the SWIR 90 m in the TIR	250 m (2 bands), 500 m (5 bands, 1000 m (29 bands)	275 m to 1.1 km	20 km	22 km
Spectral range	14 bands 0.5-12 μm	36 bands: 0.4-14 μm	4 bands: 446, 558, 672, 866 nm	3 bands: Solar: 0.3-5.0 μm Thermal: 8-12 μm Total: 0.3 to >200 μm	3 bands: 2.3 μm (CH_4), 2.4 μm (CO), and 4.7 μm (CO)
spatial coverage	60 km	2330 km	360 km	2330 km ?	640 km
repeatability	images acquired by request	daily except near the equator	6-9 days	daily	3-4 days
Stereo capability	YES	NO	YES	not relevant	NO
Main measurements	Surface composition and temperature, high resolution imagery	general land, ocean and atmospheric global studies across the solar and thermal spectrum	Application of multiview imaging for land atmospheric and ocean studies	solar, thermal and total radiation budget, cloud net radiative forcing	Global CO and CH_4 distribution

(a)

Main products	• Spectral radiances and reflectances of the Earth's surface. • Surface temperature and emissivities • Digital elevation maps from stereo images • Surface composition and vegetation maps • Cloud, sea ice, and polar ice properties • Observations of natural hazards (volcanoes, etc.)	• Surface temperature (land and ocean) • Ocean color (sediment, phytoplankton) • Global vegetation maps and monitor change • Cloud characteristics • Aerosol concentrations and properties • Temperature and moisture profiles • Snow cover and characteristics • ocean currents	• Cloud angular reflectance and effect on the planetary solar radiation budget • Tropospheric aerosols concentration and effect on the solar radiation budget. • Angular properties of surface reflectance and the impact of land processes on climate	• Cloud radiative forcing and feedbacks • Observational baseline of clear-sky radiative fluxes	• Carbon monoxide and methane concentrations in the troposphere • Carbon monoxide profiles with a resolution of 22 km horizontally and 3 km vertically with an accuracy of 10 % • Methane column in the troposphere with a resolution of 22 km and a precision of better than 1 %

(b)

a glass bowl allowing light to pass through yet trapping and retaining heat energy that radiates from the planet's surface [13]. With this work, the **Intellectual Phase** (our terminology) of climate research began. Based on Fourier's work, Claude-Servais devised the first equation for the thermal equilibrium of "light" and "dark" rays, which we know today as visible and IR radiation [13]. In 1859, Tyndall discovered that other atmospheric gases, such as methane and carbon dioxide, also block IR radiation, thereby enhancing the earth's greenhouse effect [13].

The **Quantitative Phase** of research on climate change due to greenhouse gases started after Langley invented his high-precision thermal detector—the bolometer—and began recording measurements of the lunar and solar spectra. Based upon the work and insights of Fourier and Tyndall and the precise measurements of Langley, Arrhenius became the first to hypothesize that humans can actually affect climate on a global scale. In 1896, he raised the question "is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere?" [14]. Arrhenius calculated that doubling the amount of carbon dioxide in the atmosphere would raise the earth's average temperature by 5–6 °C [14]. He estimated that industrial emissions would cause a 50% increase in atmospheric CO_2 in about 3000 years [14]. It would probably astonish Arrhenius to learn that CO_2 levels are already 30% higher a mere 100 years later, mainly due to the rapid acceleration in the use of fossil fuels [15]. Another quantitative advance in the understanding of climate change came with the theory of Milankovitch, who showed that important climate change has been driven by variations in earth's orbit [16].

We have now entered a new phase of earth systems research. We now benefit from more detailed observational records extending back into prehistory through analysis of ice cores and sediments and into the last century with bore holes and weather observations. Today and in the future, we will increasingly benefit from new techniques in atmospheric sampling and, most importantly, remote sensing. The past record shows us that climate can change substantially within decades with correlated changes in the atmospheric composition (i.e., CO_2), land surface cover (i.e., dust production), and ocean processes (i.e., thermohaline circulation [17], [18]). Recent records have yielded new insights into the short-term climatic processes that lead to large changes in weather from year to year

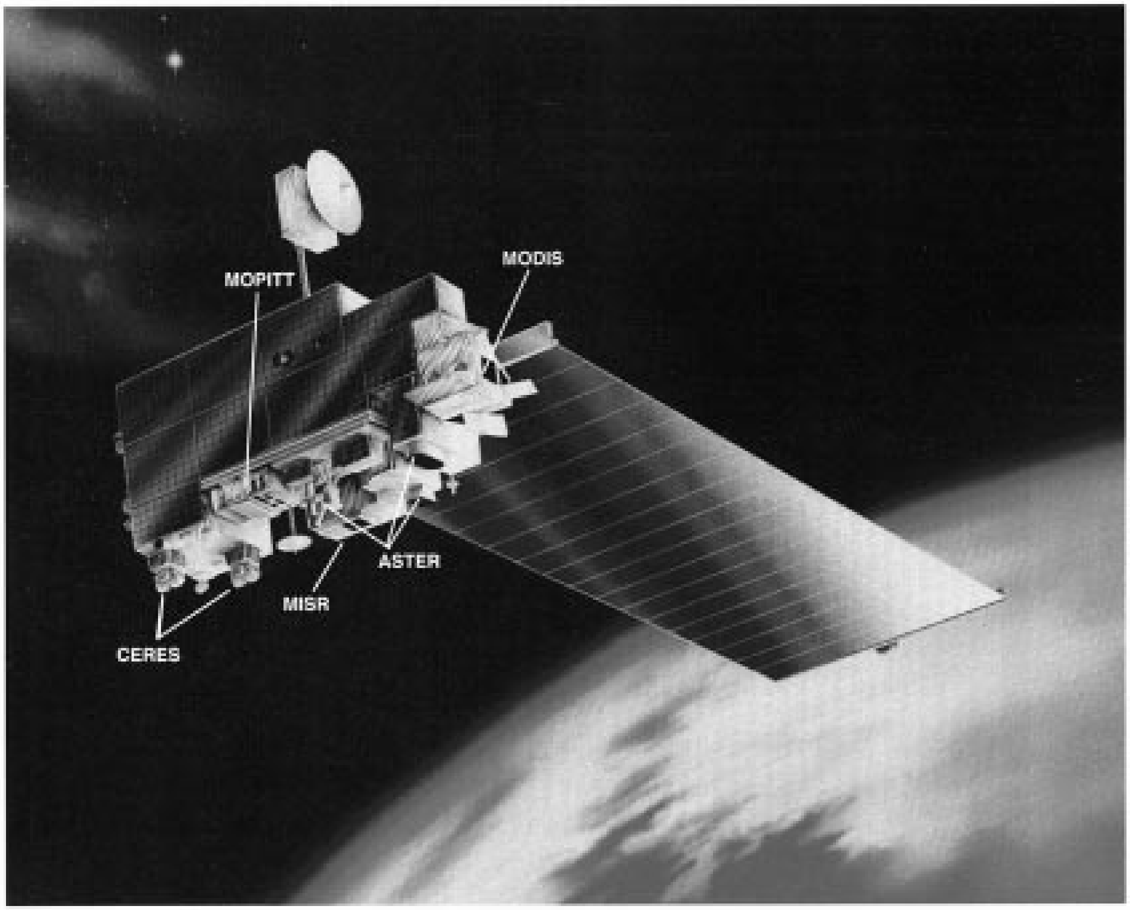

Fig. 1. Artist's rendering of EOS-AM1.

(i.e., El Niño) and have revealed that during the latter part of this century CO_2 has increased, mean surface temperature over lands and oceans has increased, and diurnal temperature range has increased, among other trends [3]. Key parameters that are sensitive to climate change typically show high temporal and spatial variability—aerosols, clouds, land and ocean biota. To study the highly varying parameters and the interactions between them, there is a need for frequent high-resolution measurements that are only possible with satellites. This notion, as well as the development of space technology, computers, and theoretical models in the last few decades, brought space-based observations to the research forefront.

The satellite record, though short (less than 20 years), has thus far contributed valuable and unique data and identified global-scale changes over this period. Specific examples of satellites' contributions are observed trends in ozone amount [19], snow extent and duration [12], vegetation response to climate change [4], human-driven changes in vegetation cover [2], and dust and smoke distributions [20], [21]. A consensus among earth scientists for investing in precise, space-based instrumentation for earth studies emerged in the mid-1980s and will be realized by NASA's EOS program with the launch of EOS-AM1 (Fig. 1) in 1998. Parallel and complementary efforts are going on in Japan (ADEOS) and Europe (ATSR, POLDER, ENVISAT). Therefore, we expect the **earth system phase** to be driven to a large degree by the collection and application of data from space-based remote sensors and their integration into climate models.

III. EOS-AM1 Science Objectives

EOS-AM1 will begin EOS' comprehensive monitoring of the interactions among the atmosphere, oceans, land, and solar and terrestrial radiation. It will also enable us to measure human impacts on these interactions. EOS-AM1 will fly in a sun-synchronous, near-polar orbit with a 10:30 a.m. equatorial crossing time to minimize the cloud effects on observations of the land and oceans. It will be followed in 2000 by EOS-PM1, which will cross the equator at 1:30 p.m. to determine diurnal variability. The main mission of EOS-AM1 is to perform high-accuracy **measurements of the main parameters that describe the state of the earth and its atmosphere and begin a long-term monitoring of the human impact on the environment**. To illustrate the importance of the EOS-AM1 mission, we use the analogy of the earth as a person who has never had a complete physical check-up and is just beginning to show some symptoms of health problems.

The specific objectives of the EOS-AM1 mission are as follows.

1) Provide a snapshot check-up of the state of the earth. **It will provide the first seasonal measurements of the following coupled parameters and processes:** land and ocean bioproductivity, land use and cover, and snow

and ice maps; global land, ocean, and air temperature—day and night; cloud macrophysics, microphysics, radiative effects, and interactions with aerosol, and the corresponding feedback and forcing of climate; radiative energy fluxes; aerosol properties and water vapor; and deforestation, fire occurrence, and emission of trace gases and smoke particles.

2) Detect human impacts on the earth and its climate. **It will improve our ability to detect human impacts, or "fingerprints," on climate [22] and enhance our long-term climate predictions** by providing updated global distributions of land use change, aerosol, water vapor, clouds and radiation, trace gases, and oceanic productivity for use in global climate models.
3) Forecast transient climatic anomalies and seasonal-to-interannual variations. **It will provide observations to improve forecasts of the timing and geographical extent of transient climatic anomalies.** It will also enhance investigations of the correlations between the regional and annual variations of clouds, aerosol, water vapor, biota in land and oceans, fires and trace gases, the radiation field, and other major impacts from El Niño, volcanic activity, and major fires.
4) Improve predictions and characterizations of natural disasters. **It will foster development of technologies for disaster prediction, characterization, and risk reduction from wildfires, volcanoes, floods, and droughts.**
5) Begin a long-term effort to monitor changes in climate and global environments. **The sensors on EOS-AM1 are uniquely designed for comprehensive earth observations and scientific analyses.** "Comprehensive" refers to the satellite's wide spatial and spectral coverage, its long temporal coverage, and the multiple disciplines to which its data will be applied.

Climate operates on cycles ranging from hours to millennia and, therefore, requires a comprehensive assessment over various periods of time. Cycles occurring from days to years are the focus of EOS-AM1. It will take a year after the launch of EOS-AM1 for the first four-dimensional (4-D) "snapshot" of our planet to emerge and possibly several years after launch to complete the first statistical evaluation of the state of the earth.

IV. Main Mission Elements

EOS-AM1 has five complementary scientific instruments that are calibrated and characterized to an unprecedented degree. These instruments will extend the measurements of their heritage sensors (e.g., AVHRR, CZCS, and ERBE), but with a higher degree of precision and will also start new measurements never before taken. The main features of these instruments are summarized in Table I. The following is a list of the EOS-AM1 instruments as well as some highlights of their new features.

1) **ASTER** will collect high spatial resolution (15-90 m), multispectral, visible through thermal IR data for local and regional process studies, including surface temperature and energy balance, and will allow mapping of soils, geology, land use, and land cover change [23];
2) EOS-AM1 will use two **CERES** instruments—one with a rotating scanning plane to determine the net cloud radiative forcing and earth's radiative budget with its better angular sampling [24];
3) **MISR** will provide imagery at moderate resolution (275 m to 1.1 km) at nine different look angles that will enable us to study the angular properties of scattering by surface cover, aerosol, and clouds and retrieve aerosol plume and cloud heights stereoscopically [25];
4) **MODIS** will enable a comprehensive daily evaluation of earth's lands, oceans, and atmosphere with its 36 spectral bands ranging from 250-m to 1-km resolution [26]. Some specific goals of MODIS are regional and global land cover characteristics and land cover change, ocean productivity, aerosol properties over land and ocean, precipitable water vapor, atmospheric temperature profiles, cloud droplet size, cloud height, and cloud top temperature;
5) **MOPITT** will provide global CO maps in three altitude layers and global CH_4 maps with 22-km resolution.

V. Examples of Science Questions Addressed by EOS-AM1

A. Earth's Radiation Budget

The earth's radiation budget determines the direction and speed of climate change. Any radiative forcing, such as due to change in surface reflectance or dust absorption of the terrestrial radiation, will change the earth radiative equilibrium and cause a transient temperature change. Satellite measurements have confirmed that the TOA insolation is 342 W m^{-2} and the TOA average albedo is 30% [8]. As recently as 15 years ago, earth radiation models showed that the atmosphere absorbs 20% of the incoming solar radiation, while the remaining 50% is absorbed by the earth's surface [8]. However, recent observational studies comparing data from NASA's ERBE satellite, first launched in 1984, with *in situ* surface data have found a major discrepancy between observed atmospheric transparency and that predicted by models, probably due to an additional 25 W m^{-2} absorbed by the atmosphere [8]. A missing heat source of 25 W m^{-2} has significant implications for global climate [8]. The CERES instrument [27], an improvement over ERBE in both its measurement capabilities and its accuracy, will conduct rigorous radiation measurements that will be used to understand this discrepancy. CERES will have the ability to measure the earth's total radiation budget by using two separate channels to measure both the reflected incoming shortwave solar radiation and emitted longwave thermal radiation [24]. Additionally, CERES will have a third channel for measuring total radiation from 0.3 to 200 μm. While one CERES instrument on EOS-AM1 will scan across track, the second will scan on a rotating plate for more complete coverage of the two-dimensional (2-D) angular distribution of the radiation field. These measurement capabilities will enable study of cloud and clear sky radiative forcings and feedbacks. The main advantage of EOS-AM1 is that CERES data are taken simultaneously from the same point in space, together with the higher spatial and spectral resolution measurements of MODIS, MISR, and MOPITT. This will enable relating the variation in the energy budget with variations in clouds, aerosol, land cover, atmospheric composition, and ocean properties. We expect to gain new insights into the specific processes by which clouds modulate the shortwave and longwave components of earth's radiation budget [28]. Long-term measurements from EOS-AM1 and follow-up missions will establish the variations in the cloud properties, due to human impact (via aerosol, which cause forcing) and the climate change (changes in dynamics and evaporation, which cause feedback), and their impact on the net radiative forcing.

B. Sources and Sinks of Greenhouse Gases

By far, water vapor is the most significant greenhouse gas for absorbing and reemitting terrestrial radiation. Although it is the most abundant atmospheric gas, water vapor is also the most variable and, therefore, presents the greatest uncertainty regarding its impact on climate. Water vapor, CO_2, and clouds account for 90–95% of our planet's retained heat energy [10]. Without these atmospheric constituents our planet's average temperature would be about 33 K colder [10]. The greater the temperature at the earth's surface (particularly at ocean surfaces), the more water evaporates into the atmosphere, so that in a warming trend we can expect a positive feedback loop that can amplify climate change. Model results suggest that water vapor feedback alone enhances the greenhouse effect by about 1% per degree of warming [10]. Yet it is unclear whether changes in the hydrological cycle will speed up global warming by increasing water vapor concentrations at mid and high altitudes [29], or counteract it by forming more low clouds to shade the surface, having a cooling effect. On average, water vapor resides in the atmosphere only a few days before falling to the surface as precipitation, so the water vapor content of the atmosphere adjusts quickly to changes in surface temperature. Globally, evaporation balances precipitation, so greater surface temperature results in more extreme precipitation and severe weather events. Recent studies based on data collected from 1900 to 1988 show that precipitation amounts have increased at a rate of 2.4 mm per decade [30].

With three near-IR spectral bands and with an array of IR bands, MODIS will measure the global distribution of tropospheric water vapor, enabling us to directly observe the dynamic positive feedback loop involving surface temperature and water vapor. The total precipitable water vapor will be measured using the near-IR bands mainly over the land; additionally, water vapor will be measured at two different levels in the troposphere by MODIS' thermal IR bands. Correlative analyses with MODIS and TRMM data will hopefully yield enhanced models for more accurately predicting severe precipitation and forecasting flood events. By combining MODIS' and MISR's simultaneous cloud measurements with CERES' measurements of the impacts of variations of water vapor on the radiation budget, EOS-AM1 will provide new information on the water vapor feedback.

Carbon dioxide is the key anthropogenic greenhouse gas. Like water vapor, it absorbs and reemits longwave terrestrial radiation and is naturally present in abundance throughout the atmosphere. Carbon dioxide levels have increased by 30% since the 1700's [1]. Due to its long lifetime in the atmosphere, it takes a century for the atmosphere to establish a new balance in response to an increase in CO_2 emissions. In addition to anthropogenic net inputs, atmospheric CO_2 levels are also determined by fluxes that occur between the biosphere and oceans. Atmospheric measurements of CO_2 reveal seasonal variations as a result of the activity of the terrestrial biosphere. The seasonal signal is closely correlated to the seasonality of green vegetation as measured from satellites [6]. The amplitude of the CO_2 drawn down varies from year to year and seems to result from climate-driven changes in terrestrial and ocean fluxes [7]. Over at least the last decade, roughly half of the anthropogenically produced CO_2 does not remain in the atmosphere, but dissolves into the oceans or is taken up by terrestrial vegetation [31]–[33]. Recent work using the satellite record of the 1980's show 1) a trend of increased vegetation growth in parts of the northern hemisphere suggesting a link between growth and the terrestrial carbon sink [4] and 2) the net flux of CO_2 from the terrestrial biosphere varies depending on climate and biogeochemistry [12]. This signal, however, has been difficult to identify because of problems associated with instrument calibration, orbital drift, and atmospheric interference.

Oceans account for half of the absorption of anthropogenic CO_2 from the atmosphere and, together with the biosphere, produce climate-driven interannual variation in atmospheric CO_2 content [34]. The ocean represents by far the largest pool (greater than 90% of the active nongeologic carbon pool). Increasing ocean temperature associated with greenhouse warming may cause net outgassing of CO_2 to the atmosphere, as would disruption of the north Atlantic thermohaline circulation [9].

EOS-AM1 and follow-up missions will help us study the poorly understood responses of terrestrial and marine ecosystems to rising CO_2 levels, in the presence of rising surface temperature and natural climate variability. By coupling ground-based CO_2 measurements with data from MODIS, MISR, and CERES, we will be able to characterize the responses of these systems to changes in the global carbon cycle and, hopefully, more accurately predict how rising CO_2 levels will affect surface temperature and biological productivity on land and in the oceans as well as changes in the energy budget. The EOS-AM1 mission was designed in part to overcome the problems associated with calibration, orbital drift, viewing and illumination angle effects, clouds, and atmospheric aerosols [35] that limit the accuracy of AVHRR-based measurements of vegetation cover.

Methane is another key greenhouse gas. Its sources include northern wetlands, ruminant animals, and natural gas leakages; however, the strengths of these individual sources are poorly known [36]. Methane is increasing in the atmosphere at a rate of about 1% per year, but the source of this increase is uncertain [36]. Since changes in atmospheric methane can potentially have a significant effect on climate, it is important to measure its concentrations and source strengths on a sustained basis. Using correlation spectroscopy, whereby a cell of the gas to be measured is used as an optical filter in the

IR to measure the signal from the same gas in the atmosphere [52], [53], MOPITT will provide global measurements of methane in the troposphere at a resolution of 22 km.

Measurements of global CO profiles was identified by the World Meteorological Organization (WMO) as being critically important for a better understanding of global change. Carbon monoxide controls the atmospheric concentrations of oxidants, thus affecting the ability of the atmosphere to clean itself from the ongoing generation of high levels of harmful tropospheric ozone from biomass burning and urban smog [54]. MOPITT's measurement of CO will help us to better understand how the troposphere interacts with vegetation emissions and with pollution from biomass burning and urban regions. The primary sources of CO include natural oxidation of methane (also measured by MOPITT) and terpenes, biomass burning, and fossil fuel burning by cars. By far, the major sink of CO is oxidation by OH and, to a much lesser extent, removal by soils [36]. MOPITT's CO measurements, taken together with MODIS' and MISR's measurements of variability in the anthropogenic sources, will be used to study CO sources and sinks and to give new insights into the processes by which chemical reactions occur in the troposphere. It is expected to improve four-dimensional (4-D) models of the transport mechanisms by which unusually large concentrations may be traced back to their sources.

C. Clouds' and Aerosols' Impacts on Climate

During the day, clouds have a cooling effect on the earth's surface by reflecting incoming sunlight. Conversely, at night, clouds have a warming effect by containing the heat energy that radiates upward from the surface toward outer space. As global temperatures increase, it is possible that more water will evaporate from the surface causing more clouds to form, thereby having an offsetting cooling effect. But, so far, the evidence shows that, although there has been an observed increase in global cloud cover to help cool the surface during the day, in the presence of higher levels of greenhouse gases, the net effect is warming.

Recent studies have confirmed a relationship between low-level cloud formation and sea surface temperature. From 1952 to 1981, there was a significant downward trend in sea surface temperature in the midlatitude Pacific and Atlantic oceans, accompanied by a significantly upward trend in the abundance of low clouds [37]. Yet, since the early 1980's, data show that this trend has reversed—the oceans are warming while low cloud amounts are decreasing in the midlatitudes [37]. This relationship is still not fully understood, but EOS-AM1 data will yield new insights. CERES will directly measure the solar and IR radiative forcing of these low-level clouds, while MODIS, MISR, and ASTER will, simultaneously, measure the cloud properties inside each CERES pixel—cloud fraction, reflectance, top temperature, droplet size, and horizontal and vertical structure. MODIS, with its wide spectral range (0.42–14.2 μm), frequent global coverage (1–2 days revisit), and two high spatial resolution channels (250 m) will enable unprecedented global monitoring of atmospheric water vapor and aerosol particles, in addition to the clouds they form. MISR, and in some limited cases, ASTER, will provide stereo imagery that will enable better classification of clouds as well as higher resolution information on cloud structure and reflectivity than was previously possible.

With its 1.37-μm channel, MODIS will observe thin cirrus clouds with unprecedented sensitivity and separate them from lower clouds that are invisible in this channel. This channel not only enables measurements of the impact of cirrus clouds on the radiation budget, but it will also permit us to "correct" for the presence of cirrus in remote-sensing scenes used to examine surface or lower level features.

The recent IPCC report shows aerosols to be a source of great uncertainty about climate forcing due to their effect on solar radiation, both directly and through their role in cloud formation [28]. The most significant sources of atmospheric aerosols are windblown dust from arid or desert regions, industrial and urban emissions, large-scale biomass burning, and volcanic eruptions. Aerosols affect climate in two ways, both of which tend to cause cooling at the surface. First, the particles alter the radiative properties of the atmosphere by scattering or absorbing incoming solar radiation. Second, they modify cloud droplet size and affect their formation and lifetime, acting as cloud condensation nuclei for attracting water vapor. Aerosol modification of cloud droplet size can enhance their reflection of sunlight, thus generating a negative climate forcing [21]. Much work has been done over the past three decades to identify the major aerosol types—as a function of season and location—and to characterize their properties and impacts on the radiation budget and clouds. However, the high variability of aerosol loading, size, and composition, prohibits systematic global measurements without highly accurate spectral satellite data [28]. Using two different measurement techniques, MODIS, using its wide solar spectral range (0.41–3.7 μm), and MISR, using its nine simultaneous multiangular views, will collect these needed global aerosol data. Together with networks of ground-based instrumentation for remote and *in situ* measurements, the satellite data will be used to quantify aerosol's role in global change.

Ice core samples show that there were much higher levels of atmospheric dust and lower levels of CO_2 during the last glacial maximum—about 30 times more continental dust [38] and about 40% less CO_2 [1]. This evidence supports the logic that aerosols play a negative radiative forcing role in climate change. Yet, as was recently theorized, aerosols may also play another, less-direct role in negative radiative forcing. Climate models suggest that a global warming trend may cause the interior regions of continents to become more arid and, as a result, there will be more iron-rich windblown continental dust settling in the oceans. It has been demonstrated that there is a lack of iron in large regions of the oceans, limiting the photosynthetic absorption of atmospheric CO_2 [39], despite the abundance of other nutrients; e.g., nitrates. "Seeding" experiments have shown that adding iron to these waters greatly increases phytoplankton productivity [40]. Therefore, more abundantly available iron-rich continental dust will contribute to more robust marine primary productivity, thereby enhancing its ability to serve as a CO_2 sink [40]. Perhaps this could explain (at least in part) why during the last glacial maximum, there was a measured increase in atmospheric dust and a decrease in CO_2. These considerations demonstrate the uncertainties in understanding climate and the need to measure diverse parameters of the earth system to understand the relationships between its biochemical and physical processes that together determine the state and climate of the planet. With their diverse suite of instruments, EOS-AM1 and Landsat-7 will provide an unprecedented ability to monitor the impacts that surface changes have on windblown continental dust distributions, measure the impacts these aerosols have on primary productivity in the oceans, and in turn enhance correlative studies on the impacts of increased (or decreased) marine productivity on CO_2 levels.

D. Coupling with the Oceans

Covering more than 70% of our planet and holding 97% of earth's surface water, the oceans have been called "the heat engine of global climate" due to their influence on the timing and patterns of climate change. As discussed above, the oceans and atmosphere interact dynamically to exchange heat, momentum, and gases—all of which have profound influences on weather patterns and biological productivity on land and in the oceans. Reliable sea surface temperature measurements from space-based sensors has been a goal of oceanographers since the late 1960's that has been frustrated by radiometer window placement, radiometer noise, quality of prelaunch instrument characterization, inflight calibration quality, viewing geometry, and lack of atmospheric correction [41]. With its low noise ($<$0.05 K between 10–12 μm) and narrow, well-placed spectral bands in the 3.7–4.2-μm range, MODIS will measure sea surface temperature anomalies with greater accuracy ($\leq$0.5 K) than was ever before possible from a space-based platform. These data will enable a better understanding of ocean-atmosphere exchanges—particularly during El Niño phenomena. Ocean water has a high heat capacity and even small changes in ocean temperature can have major effects on weather and climate. The devastating El Niño of 1981–1982, for example, showed a temperature difference of only 5°, yet was estimated by NOAA to have contributed to some $8 billion in damages to human resources worldwide by causing floods in some regions and droughts in others [42].

MODIS measurements of global sea surface temperatures can be correlated with measurements of fluorescence and concentrations of chlorophyll a, which are used to estimate the rate of biological productivity in ocean waters. These parameters are critical for deriving rates of productivity and monitoring areal distributions and concentrations of phytoplankton—the foundation of the marine food chain. With its six spectral bands centered at 412, 443, 488, 531, 551, and 667 nm, respectively, MODIS will measure concentrations of chlorophyll a, the biochemical used by phytoplankton during photosynthesis. Three other MODIS bands centered at 667, 678, and 748 nm, respectively, will provide measurements of fluorescence—the emission of energy in the blue region of the spectrum, used by MODIS to derive the rate of photosynthesis. This suite of fluorescence bands [43] is available now on a global satellite sensor for the first time in MODIS and will enable us to improve our estimates of primary productivity in the ocean.

By measuring water-leaving radiance (ocean color) variations, MODIS and MISR (using its 446.4-nm and 557.5-nm bands) will enable us to infer certain parameters of the ocean's biological and chemical composition, such as the abundance and variability of phytoplankton and sediments. The MODIS team will employ remote-sensing algorithms similar to those developed for the SeaWiFS project. MODIS' measurements of ocean color will be complemented by those of other remote sensors. Due to sun glint over a portion of its viewing swath, some MODIS oceanic imagery will not be useful. But, combining data from MODIS and SeaWiFS, as suggested by Gregg and Woodward [44], would improve ocean coverage. This gap in ocean color data can also be partially filled by MISR, which images the surface at nine different look angles. Additionally, MISR will provide independent measurements of aerosols that are crucial for corrections of both ocean color measurements and land surface reflectance. Moreover, coupling MODIS and MISR data with those of TRMM and Topex-Poseidon should lead to improved models of ocean, atmosphere, and land interactions.

As noted above, the ocean is a sink for atmospheric CO_2, which is used by phytoplankton in photosynthesis. The amount of CO_2 used depends heavily on upwelling ocean currents, which circulate nutrients to the upper layers where sunlight is also abundant, allowing phytoplankton to thrive. Some fraction of particulate carbon produced by the phytoplankton sinks to the ocean floor, which is a long-term sink for carbon. This fraction that settles to the bottom annually is a source of significant uncertainty in the global carbon budget and may be comparable to terrestrial CO_2 sinks. Over geological time (eons), 99.5% of carbon on earth is found in features of marine sediments [18].

Algorithms have been developed for using MODIS data to quantify the aerial extent of snow and ice on earth's surface and measure ongoing changes in the cryosphere [45]. By cross comparing these data with data from CERES, MISR, ASTER, Topex-Poseidon, and Landsat-7, it will be possible to quantify the causes and effects of changes to sea surface temperatures, changing sea ice extents, ocean currents, precipitation patterns, and air temperatures.

E. Land Use Change

Global change may seem more "obvious" when the patterns on earth's landscapes are considered. Human population has tripled in the last century [46], leading to burgeoning urban centers that can be easily seen from space at night as growing clusters of diamonds of light. To feed the need for space, energy, and nutrition, humans have changed the surface cover of 40% of the earth's lands [2]. Biomass burning—the most widely employed method for clearing away forests for agriculture, cattle grazing, or urban development—has quadrupled [2]. Atmospheric concentrations of CO_2 and other trace gases has increased by 30% as a result of human industry [2].

Using MODIS, MISR, ASTER, and Landsat-7 data, we will be able to construct improved global vegetation maps to provide up-to-date estimates of the distribution of earth's major vegetation types. We will also be able to ascertain whether the vegetation is healthy or under stress. By globally monitoring subtle vegetation responses to stress in the biosphere—such as increases in tropospheric ozone or decreases in stratospheric ozone—we will learn about both the nature and severity of the stress. We will, for example, enhance global famine early warning systems with better predictions and assessments of freeze, flood, or drought damage to croplands. Timely global information on the overall status of crops throughout the growing season is vital for monitoring the world's food resources, yet this information is currently available for relatively few areas. MODIS and MISR data will be used to develop global LAI estimates and calculate mass and energy exchange between vegetated surfaces and the atmosphere [45]. This will improve global estimates of carbon storage in terrestrial plants, which currently vary by as much as an order of magnitude.

The ability to track changes in land cover will be essential in modeling global change. Burning vast regions of forest has a twofold effect: 1) it releases stored carbon and particulates into the atmosphere and 2) it eliminates vegetation that would otherwise be absorbing carbon from the atmosphere. On the other hand, there are instances where "controlled" forest fires are desirable. In some parts of Montana, for example, fire fighters have been so efficient at fighting wildfires over the last century that there is now a vast reserve of stored fuel in the form of dead biomass collecting on the ground [56]. These regions have become like large tinder boxes that are now highly susceptible to wildfires. Using Normalized Difference Vegetation Index (NDVI) data and surface temperature data, the MODIS team plans to provide a regularly updated global map of regions that are dry and therefore susceptible to wildfire [45]. An experimental version of the fire susceptibility product is being computed on a weekly basis for 11 of the western United States using AVHRR data processed by EROS Data Center [56].

Models to predict climate change hinge on our ability to characterize land cover parameters—such as elevation, surface roughness, albedo, and fluxes of sensible and latent heat. MODIS, CERES, MISR, ASTER, and Landsat-7 will measure these parameters with unprecedented accuracy. A collection of articles from members of the MISR Instrument Team introduce the capabilities of MISR for determining ocean and land properties [48], [49]. Descriptions of the ASTER Instrument Team's geophysical products of topography [50] and land surface temperature [51] can also be found in this special issue.

Finally, a thermal alarm algorithm has been built into the process flow of MODIS data that will indicate the presence of significant heat sources on the surface. These heat sources may either be large forest fires or volcanic activity. This alarm will not only flag thermal events of scientific interest for closer scrutiny, but could potentially help warn populations living near an active volcano of an impending eruption.

VI. Validation

In both the prelaunch and postlaunch periods of EOS-AM1, EOS Instrument Team Members and interdisciplinary science investigators will conduct scientific field campaigns to verify the quality and long-term stability of the EOS sensors' measurements as well as the validity of the derived geophysical data products. The magnitudes of any uncertainties and errors in EOS-AM1 data products must be quantified, on both spatial and temporal scales, to ensure that the data are scientifically credible and maximally useful. Understanding the uncertainties and errors is also essential for future improvement of the algorithms and earth observing systems.

To obtain the necessary correlative observations required for validation, the EOS Program will use a four-pronged approach that incorporates the following:

1) surface-based (*in situ*) radiance observations and measurements at specific test sites obtained as part of the EOS interdisciplinary, instrument, and validation teams' investigations;
2) field experiments conducted by EOS interdisciplinary, instrument, and validation teams as well as participation in, and support of, nationally and internationally coordinated field programs;
3) coordination with national and international observation sites and networks, such as the DoE ARM Program, NSF LTER sites, and the WCRP BSRN; and
4) Airborne remote-sensing measurements using specifically designed EOS instrument simulators, such as the MAS, MASTER, and AirMISR [55] as well as community airborne instruments, such as AVIRIS.

These highly focused validation activities will range from vicarious calibration of the basic radiance measurements to validation of the higher order biogeophysical products, such as land cover, ocean chlorophyll content, net primary productivity, and the planetary energy budget—including components of the atmosphere and surface energy budgets. Validation of the EOS-AM1 Science Data Products encompasses measurements and comparisons made on local to regional to global scales, including intercomparison of various satellite-derived parameters and the incorporation of satellite-derived information into models of the earth system and its components.

VII. Conclusion

NASA's Earth Science Enterprise, together with space agencies around the world, is funding a concerted scientific effort to answer the myriad of questions about the causes and effects of global change. The flagship of NASA's effort, EOS-AM1, is scheduled to launch in 1998. Once in orbit, it will be the most advanced, best-calibrated tool for measuring simultaneously from the same viewpoint in space the main parameters associated with global climate change. This article has provided an overview of some of the planned applications of the data from this new scientific tool. No doubt there will be many new applications that are not addressed here, some of which will be serendipitous in nature. Subsequent articles in this issue will address in more detail the performance capabilities of the sensors aboard this spacecraft as well as more adequately describe the science disciplines to which EOS-AM1 data will be applied.

REFERENCES

[1] D. Hartmann *et al.*, "Reports to the nation on our changing planet: Our changing climate," *NOAA Brochure*, vol. 4, Fall 1997.

[2] P. M. Vitousek *et al.*, "Human domination of earth's ecosystems," *Science*, vol. 277, pp. 494–499, 1997.

[3] Climate Change 1995, The IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change, http://www.ipcc.ch.

[4] R. B. Myneni *et al.*, "Increased plant growth in the northern high latitudes from 1981–1991," *Nature*, vol. 386, pp. 698–702, 1997.

[5] B. H. Braswell *et al.*, "The response of global terrestrial ecosystems to interannual temperature variability," *Science*, vol. 278, pp. 870–872, 1997.

[6] C. J. Tucker *et al.*, "Relationship between atmospheric CO_2 variations and satellite derived vegetation index," *Nature*, vol. 319, pp. 195–199, 1986.

[7] C. D. Keeling *et al.*, "Increased activity of northern vegetation inferred from atmospheric CO_2 measurements," *Nature*, vol. 277, pp. 146–149, 1996.

[8] V. Ramanathan and A. M. Vogelmann, "Greenhouse effect, atmospheric solar absorption and the Earth's radiation budget: From the Arrhenius–Langley era to the 1990s," *Ambio*, vol. 26, pp. 38–46, 1997.

[9] W. Broecker, "Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance," *Science*, vol. 278, pp. 1582–1588, 1997.

[10] V. Ramanathan, "Trace gas greenhouse effect and global warming: Underlying principles and outstanding issues," Volvo Environmental Prize Lecture, 1997.

[11] P. Y. Groisman *et al.*, "Observed impact of snow cover on the heat balance and the rise of continental spring temperatures," *Science*, vol. 263, pp. 198–200, 1994.

[12] B. H. Braswell *et al.*, "The response of global terrestrial ecosystems to interannual temperature variability," *Science*, vol. 278, pp. 870–873, 1997.

[13] H. Rodhe *et al.*, "Svante Arrhenius and the greenhouse effect," *Ambio*, vol. 26, pp. 2–5, 1997.

[14] S. Arrhenius, "On the influence of carbonic acid in the air upon the temperature of the ground," *Phil. Mag. J. Sci.*, vol. 41, p. 251, 1896.

[15] H. Rodhe and R. Charlson, Guest Editorial, *Ambio*, vol. 26, p. 1, 1997.

[16] M. Milankovitch, "Canon of insolation and ice-age problem," in *Israel Progr. Sci. Translat.*, U.S. Dept. of Commerce and the National Science Foundation, Washington, DC, 1969 (original pub. 1941).

[17] J. T. Overpeck *et al.*, "Deglacial changes in ocean circulation from an extended radiocarbon calibration, *Nature*, vol. 391, pp. 65–68, 1998.

[18] H. Kitagawa and J. van der Plicht, "Atmospheric radiocarbon calibration to 45,000 yr B.P.: Late glacial fluctuations and cosmogenic isotope production," *Science*, vol. 279, pp. 1187–1190, 1998.

[19] R. S. Stolarski *et al.*, "Total ozone trends deduced from Nimbus 7 TOMS Data," *Geophys. Res. Lett.*, vol. 18, pp. 1015–1018, 1991.

[20] C. Moulin *et al.*, "Long-term daily monitoring of Saharan dust load over ocean using Meteosat ISCCP-B2 data," *J. Geophys. Res.*, vol. 102, pp. 16 947–16 969, 1997.

[21] Y. J. Kaufman and R. S. Fraser, "The effect of smoke particles on clouds and climate forcing," *Science*, vol. 277, pp. 1636–1639, 1997.

[22] B. D. Santer *et al.*, "A search for human influence on the thermal structure of the atmosphere," *Nature*, vol. 382, pp. 39–46, 1996.

[23] Y. Yamaguchi, A. B. Kahle, H. Tsu, T. Kawakami, and M. Pniel, "Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)," this issue, pp. 1062–1071.

[24] B. A. Wielicki, B. R. Barkstrom, B. A. Baum, T. P. Charlock, R. N. Green, D. P. Kratz, R. B. Lee, III, P. Minnis, G. L. Smith, T. Wong, D. F. Young, R. D. Cess, J. A. Coakley, Jr., D. A. H. Crommelynck, L. Donner, R. Kandel, M. D. King, A. J. Miller, V. Ramanathan, D. A. Randall, L. L. Stowe, and R. M. Welch, "Clouds and the Earth's Radiant Energy System (CERES): Algorithm overview," this issue, pp. 1127–1141.

[25] D. J. Diner, J. C. Beckert, T. H. Reilly, C. J. Bruegge, J. E. Conel, R. A. Kahn, J. V. Martonchik, T. P. Ackerman, R. Davies, S. A. W. Gerstl, H. R. Gordon, J.-P. Muller, R. B. Myneni, P. J. Sellers, B. Pinty, and M. M. Verstraete, "Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview," this issue, pp. 1072–1087.

[26] W. L. Barnes, T. S. Pagano, and V. V. Salomonson, "Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1," this issue, pp. 1088–1100.

[27] R. B. Lee, III, B. R. Barkstrom, H. C. Bitting, D. A. H. Crommelynck, J. Paden, D. K. Pandey, K. J. Priestley, G. L. Smith, S. Thomas, K. L. Thornhill, and R. S. Wilson, "Prelaunch calibrations of the Clouds and the Earth's Radiant Energy System (CERES) tropical rainfall measuring mission and Earth Observing System morning (EOS-AM1) spacecraft thermistor bolometer sensors," this issue, pp. 1173–1185.

[28] M. D. King *et al.*, "Remote sensing of cloud, aerosol, and water vapor properties from the Moderate Resolution Imaging Spectroradiometer (MODIS)," *IEEE Trans. Geosci. Remote Sensing*, vol. 30, pp. 2–27, Jan. 1992.

[29] R. S. Lindzen, "On the scientific basis for global warming scenarios," *Environ. Pollut.*, vol. 83, pp. 125–134, 1994.

[30] A. Dai *et al.*, "Surface observed global land precipitation variations during 1900–1988," *J. Clim.*, vol. 10, pp. 2943–2962, 1997.

[31] P. P. Tans *et al.*, "Observational constraints on the global atmospheric CO_2 budget," *Science*, vol. 247, pp. 1431–1438, 1990.

[32] P. Ciais *et al.*, "A large northern-hemisphere terrestrial CO_2 sink indicated by the C-13/C-12 ratio of atmospheric CO_2," *Science*, vol. 269, pp. 1098–1102, 1995.

[33] A. S. Denning *et al.*, "Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota," *Nature*, vol. 376, pp. 240–243, 1995.

[34] C. D. Keeling *et al.*, "Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980," *Nature*, vol. 375, pp. 666–670, 1995.

[35] S. O. Los *et al.*, "A global 1 degree $\times$ 1 degree NDVI data set for climate studies derived from the GIMMS continental NDVI data," *Int. J. Remote Sensing*, vol. 15, pp. 3493–3518, 1994.

[36] J. Gille *et al.*, MOPITT Algorithm Theoretical Basis Document: Retrieval of Carbon Monoxide Profiles and Column Amounts of Carbon Monoxide and Methane from MOPITT Radiances (Level 1-2), Dept. Phys., Univ. Toronto, Toronto, Ont., Canada, 1996; ftp://eospso.gsfc.nasa.gov/ATBD/REVIEW/MOPITT/ATBD-MOP-02/atbd-mop-02.pdf

[37] J. R. Norris and C. Leovy, "Interannual variability in stratiform cloudiness and sea surface temperature," *J. Clim.*, vol. 7, pp. 1917–1925, 1994.

[38] Y. L. Yung *et al.*, "Dust: A diagnostic of the hydrologic cycle during the last glacial maximum," *Science*, vol. 271, pp. 962–963, 1996.

[39] A. Longhurst, "Iron grip on export production," *Nature*, vol. 379, pp. 585–586, 1996.

[40] K. H. Coale *et al.*, "Control of community growth and export production by upwelled iron in the equatorial Pacific Ocean," *Nature*, vol. 379, pp. 621–624, 1996.

[41] O. Brown *et al.*, "MODIS infrared sea surface temperature algorithm theoretical basis document," Dept. Meteorol. Phys. Oceanog., Univ. Miami, Coral Gables, FL, 1996; ftp://eospso.gsfc.nasa.gov/ATBD/REVIEW/MODIS/ATBD-MOD-25/atbd-mod-25.pdf

[42] J. M. Wallace and S. Vogel, "Reports to the nation on our changing planet: El Niño and climate prediction," *NOAA Brochure*, vol. 3, spring 1994.

[43] W. E. Esaias, M. R. Abbott, I. Barton, O. W. Brown, J. W. Campbell, K. L. Carder, D. K. Clark, R. L. Evans, F. E. Hoge, H. R. Gordon, W. P. Balch, R. Letelier, and P. J. Minnett, "An overview of MODIS capabilities for ocean science observations," this issue, pp. 1250–1265.

[44] W. W. Gregg and R. H. Woodward, "Improvements in coverage frequency of ocean color: Combining data from SeaWiFS and MODIS," this issue, pp. 1350–1353.

[45] C. O. Justice, E. Vermote, J. R. G. Townshend, R. Defries, D. Roy, D. K. Hall, V. V. Salomonson, J. L. Privette, G. Riggs, A. Strahler, W. Lucht, R. B. Myneni, Y. Knyazikhin, S. W. Running, R. R. Nemani, Z. Wan, A. R. Huete, W. van Leeuwen, R. E. Wolfe, L. Giglio, J.-P. Muller, P. Lewis, and M. J. Barnsley, "The Moderate Resolution Imaging Spectrometer (MODIS): Land remote sensing for global change research," this issue, pp. 1228–1249.

[46] U.S. Census Bureau, "U.S. Census Bureau home page," World Wide Web site, http://www.census.gov/cgi-bin/ipc/popclockw, 1998.

[47] H. Fujisada, F. Sakuma, A. Ono, and M. Kudoh, "Design and preflight performance of ASTER instrument protoflight model," this issue, pp. 1152–1160.

[48] V. M. Jovanovic, M. M. Smyth, J. Zong, R. Ando, and G. W. Bothwell, "MISR photogrammetric data reduction for geophysical retrievals," this issue, pp. 1290–1301.

[49] J. V. Martonchik, D. J. Diner, B. Pinty, M. M. Verstraete, R. B. Myneni, Y. Knyazikhin, and H. R. Gordon, "Determination of land and ocean reflective, radiative, and biophysical properties using multiangle imaging," this issue, pp. 1266–1281.

[50] R. Welch, T. Jordan, H. Lang, and H. Murakami, "ASTER as a source for topographic data in the late 1990's," this issue, pp. 1282–1289.

[51] A. Gillespie, S. Rokugawa, T. Matsunaga, J. S. Cothern, S. Hook, and A. B. Kahle, "A temperature and emissivity separation algorithm for

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images," this issue, pp. 1113–1126.
[52] R. Bouchard and J. Giroux, "Test and qualification results on the MOPITT flight calibration sources," *Opt. Eng.*, vol. 36, pp. 2992–3000, 1997.
[53] M. W. Smith, "Method and results for optimizing the MOPITT methane bandpass," *Appl. Opt.*, vol. 36, pp. 4285–4291, 1997.
[54] J. R. Drummond and G. S. Mand, "The measurements of pollution in the troposphere (MOPITT) instrument: Overall performance and calibration requirements," *J. Atmos. Ocean. Technol.*, vol. 13, pp. 314–320, 1996.
[55] D. J. Diner, L. M. Barge, C. J. Bruegge, T. G. Chrien, J. E. Conel, M. L. Eastwood, J. D. Garcia, M. A. Hernandez, C. G. Kurzweil, W. C. Ledeboer, N. D. Pignatano, C. M. Sarture, and B. G. Smith, "The airborne Multi-angle Imaging SpectroRadiometer (AirMISR): Instrument description and first results," this issue, pp. 1339–1349.
[56] Steve W. Running, private communication, 1997.

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K. Jon Ranson, for a photograph and biography, see this issue, p. 1040.

G. James Collatz, for a photograph and biography, see this issue, p. 1040.